Microwave modulation of electron heating and Shubnikov-de Haas oscillation in two-dimensional electron systems

X.L. Lei and S.Y. Liu
Department of Physics, Shanghai Jiaotong University, 1954 Huashan Road, Shanghai 200030, China

Recently discovered modulations of Shubnikov-de Haas oscillations in microwave-irradiated two-dimensional electron systems are shown to arise from electron heating induced by the radiation. The electron temperature, obtained by balancing the energy absorption from the microwave field and the energy dissipation to the lattice through realistic electron-phonon couplings, exhibits resonance. The modulation of the Shubnikov de Haas oscillation and the suppression of magnetoresistance are demonstrated together with microwave-induced resistance oscillation, in agreement with experimental findings.

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Since the discovery of microwave induced magnetorersistance oscillations (MIMOs) in high-mobility two-dimensional (2D) electron gas (EG)[1,2,3,4] tremendous experimental[5,6,7,8,9,10,11,12,13] and theoretical[14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30] interest has been attracted to radiation related magnetotransport in 2DEG. Most of previous investigations were focused on the range of low magnetic fields $\omega_c/\omega \leq 1$ (ω_c stands for the cyclotron frequency) subject to a radiation of frequency $\omega/2\pi \leq 100\,$GHz, where MIMOs show up strongly and Shubnikov-de Haas oscillations (SdHOs) are relatively weak. Recent observations clearly show that the amplitudes of SdHOs are also strongly affected by the microwave radiation in both the low ($\omega_c/\omega \leq 1$) and the high ($\omega_c/\omega > 1$) magnetic field ranges.[10,11,12,13]

We propose that these SdHO modulations come from the electron heating induced by the microwave radiation. By carefully calculating the electron temperature based on the balance of the energy absorption from the radiation field and the energy dissipation to the lattice through the electron-phonon interactions, we reproduce all of the interesting phenomena of MIMOs and SdHO modulations observed in the experiments.

Consider that a dc electric field $\mathbf{E}_0$ and a high frequency (HF) field $\mathbf{E}(t) \equiv \mathbf{E}_s \sin(\omega t) + \mathbf{E}_c \cos(\omega t)$ are applied in a quasi-2D system consisting of $N_{\rm e}$ interacting electrons in a unit area of the x-y plane, together with a magnetic field $\mathbf{B} = (0, 0, B)$ along the z direction.

For ultra-clean, high-carrier-density electron systems in the experiments at low temperature without the onset of the quantum Hall effect, the transport under a modest radiation field can be described by the balance-equation model in terms of the time-dependent electron drift velocity $\mathbf{v}(t) = \mathbf{v}_0 - \mathbf{v}_1 \cos(\omega t) - \mathbf{v}_2 \sin(\omega t)$, together with an electron temperature $T_{\rm e}$ characterizing the electron heating.[31] They can be determined by the following force- and energy-balance equations:[32]

$$\mathbf{v}_1\omega \sin(\omega t) - \mathbf{v}_2\omega\cos(\omega t) = \frac{1}{N_{\rm e} m}\mathbf{F}(t) + \frac{e}{m}\left[\mathbf{E}_0 + \mathbf{E}(t) + \mathbf{v}(t)\times\mathbf{B}\right], \qquad (1)$$

$$N_{\rm e}\mathbf{E}_0\cdot\mathbf{v}_0 + S_{\rm p} - W = 0. \qquad (2)$$

Here m is the electron effective mass, $\mathbf{F}(t)$ is the damping force of the moving electrons,

$$S_{\rm p} = \sum_{\mathbf{q}_\parallel} \left|U(\mathbf{q}_\parallel)\right|^2 \sum_{n=-\infty}^{\infty} n\omega J_n^2(\xi)\Pi_2(\mathbf{q}_\parallel, \omega_0 - n\omega) + \sum_{\mathbf{q}} |M(\mathbf{q})|^2 \sum_{n=-\infty}^{\infty} n\omega J_n^2(\xi)\Lambda_2(\mathbf{q}, \omega_0 + \Omega_{\mathbf{q}} - n\omega) \qquad (3)$$

is the time-averaged rate of the electron energy absorption from the HF field, and

$$W = \sum_{\mathbf{q}} |M(\mathbf{q})|^2 \sum_{n=-\infty}^{\infty} \Omega_{\mathbf{q}} J_n^2(\xi)\Lambda_2(\mathbf{q}, \omega_0 + \Omega_{\mathbf{q}} - n\omega) \qquad (4)$$

is the time-averaged rate of the electron energy loss to the lattice due to electron-phonon scatterings. In the above expressions, $J_n(\xi)$ is the Bessel function of order n, $\xi \equiv \sqrt{(\mathbf{q}_\parallel\cdot\mathbf{v}_1)^2 + (\mathbf{q}_\parallel\cdot\mathbf{v}_2)^2}/\omega$; $\omega_0 \equiv \mathbf{q}_\parallel\cdot\mathbf{v}_0$, $U(\mathbf{q}_\parallel)$ and $M(\mathbf{q})$ stand for effective impurity and phonon scattering potentials, $\Pi_2(\mathbf{q}_\parallel, \Omega)$ and $\Lambda_2(\mathbf{q}, \Omega) = 2\Pi_2(\mathbf{q}_\parallel, \Omega)[n(\Omega_{\mathbf{q}}/T) - n(\Omega/T_{\rm e})]$ (with $n(x) \equiv 1/({\rm e}^x - 1)$) are the imaginary parts of the electron density correlation function and electron-phonon correlation function in the magnetic field.

Transverse and longitudinal photoresistivities are obtained directly from the dc part of the force-balance equation. The linear magnetoresistivity ($\mathbf{v}_0 \to 0$) is given by

$$R_{xx} = -\sum_{\mathbf{q}_\parallel} q_x^2 \frac{|U(\mathbf{q}_\parallel)|^2}{N_{\rm e}^2 e^2} \sum_{n=-\infty}^{\infty} J_n^2(\xi) \left.\frac{\partial \Pi_2}{\partial\,\Omega}\right|_{\Omega = n\omega} - \sum_{\mathbf{q}} q_x^2 \frac{|M(\mathbf{q})|^2}{N_{\rm e}^2 e^2} \sum_{n=-\infty}^{\infty} J_n^2(\xi) \left.\frac{\partial \Lambda_2}{\partial\,\Omega}\right|_{\Omega = \Omega_{\mathbf{q}} + n\omega}. \qquad (5)$$

The $\Pi_2(\mathbf{q}_\parallel, \Omega)$ function of the 2D system in a magnetic field can be calculated by means of Landau representation:[33]

$$\Pi_2(\mathbf{q}_\parallel, \Omega) = \frac{1}{2\pi l_{\rm B}^2}\sum_{n,n'} C_{n,n'}(l_{\rm B}^2 q_\parallel^2/2)\Pi_2(n, n', \Omega), \qquad (6)$$

$$\Pi_2(n,n',\Omega) = -\frac{2}{\pi}\int d\varepsilon\,[f(\varepsilon)-f(\varepsilon+\Omega)] \times \mathrm{Im}G_n(\varepsilon+\Omega)\mathrm{Im}G_{n'}(\varepsilon), \quad (7)$$

where $l_{\rm B}=\sqrt{1/|eB|}$ is the magnetic length, $C_{n,n+l}(Y)\equiv n![(n+l)!]^{-1}Y^l e^{-Y}[L_n^l(Y)]^2$ with $L_n^l(Y)$ the associate Laguerre polynomial, $f(\varepsilon)=\{\exp[(\varepsilon-\mu)/T_{\rm e}]+1\}^{-1}$ is the Fermi distribution function at electron temperature $T_{\rm e}$. In the case of separated levels discussed in this letter, the density of states of the n-th Landau level is modeled by a semielliptic form:[34]

$$\mathrm{Im}G_n(\varepsilon) = -(2/\Gamma^2)[\Gamma^2-(\varepsilon-\varepsilon_n)^2]^{\frac{1}{2}} \quad (8)$$

around the level center ε_n within half-width $\Gamma = (8e\omega_c\alpha/\pi m\mu_0)^{1/2}$, and $\mathrm{Im}G_n(\varepsilon)=0$ elsewhere. Here μ_0 is the linear mobility at lattice temperature T in the absence of magnetic field and α is a semiempirical parameter.

Assume that the 2DEG is contained in a thin sample suspended in a vacuum at plane $z=0$. When an electromagnetic wave illuminates the plane perpendicularly with the incident electric field $\mathbf{E}_{\rm i}(t)=\mathbf{E}_{\rm is}\sin(\omega t)+\mathbf{E}_{\rm ic}\cos(\omega t)$, the HF electric field in the 2DEG determined by the Maxwell equations is

$$\mathbf{E}(t) = \frac{N_{\rm e}e\,\mathbf{v}(t)}{2\epsilon_0 c}+\mathbf{E}_{\rm i}(t). \quad (9)$$

With this $\mathbf{E}(t)$, $\mathbf{v}_1$ and $\mathbf{v}_2$ are explicitly solved from Eq. (1) for clean systems at low temperatures.

For systems used in the experiments at temperature $T\le 1\,$K, the dominant contribution to the energy absorption $S_{\rm p}$ and photoresistivity $R_{xx}-R_{xx}(0)$ come from the impurity-assisted photon absorption and emission process. At different magnetic field strength, this process is associated with electron transition between either inter-Landau level states or intra-Landau-level states. The condition for inter-Landau level transition with impurity-assisted single-photon process[35] is $\omega>\omega_c-2\Gamma$, or $\omega_c/\omega<a_{\rm inter}=(\beta+\sqrt{\beta^2+4})^2/4$; and that for impurity-assisted intra-Landau level transition is $\omega<2\Gamma$, or $\omega_c/\omega>a_{\rm intra}=\beta^{-2}$, here $\beta=(32e\alpha/\pi m\mu_0\omega)^{\frac{1}{2}}$. To obtain the energy dissipation rate W, which is needed for calculating the electron heating, we take account of scatterings from bulk longitudinal and transverse acoustic phonons (via the deformation potential and piezoelectric couplings), as well as from longitudinal optical phonons (via the Fröhlich coupling) in the GaAs-based system. In this letter, background charged impurities are assumed to be the dominant elastic scatterers and all the calculations were carried out with the x-direction (parallel to $\mathbf{E}_0$) linearly polarized incident microwave fields $[\mathbf{E}_{is}=(E_{\rm is},0),\mathbf{E}_{ic}=0]$, using the widely accepted material and coupling parameters bulk of GaAs.[36]

Figure 1 shows the calculated energy absorption rate $S_{\rm p}$, the electron temperature $T_{\rm e}$, and the longitudinal resistivity R_{xx} as functions of ω_c/ω for a 2D system having electron density $N_{\rm e}=3.0\times10^{15}\,{\rm m}^{-2}$, linear

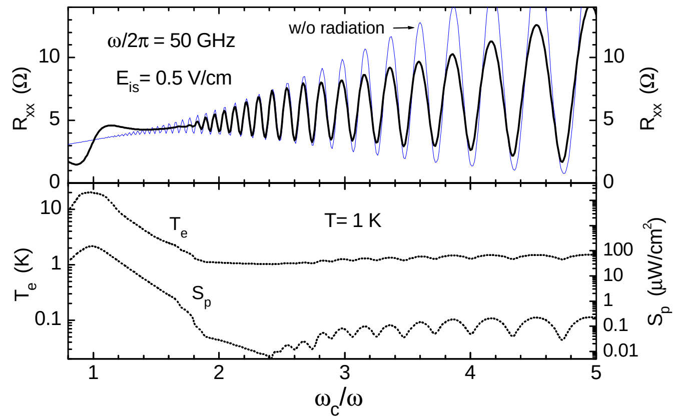

FIG. 1: The magnetoresistivity R_{xx}, electron temperature $T_{\rm e}$ and energy absorption rate $S_{\rm p}$ of a GaAs-based 2DEG with $N_{\rm e}=3.0\times10^{15}\,{\rm m}^{-2}$, $\mu_0=1000\,{\rm m}^2/{\rm Vs}$ and $\alpha=5$, subjected to an incident HF field of frequency 50 GHz with amplitude $E_{\rm is}=0.5\,{\rm V/cm}$ at lattice temperature $T=1\,K$.

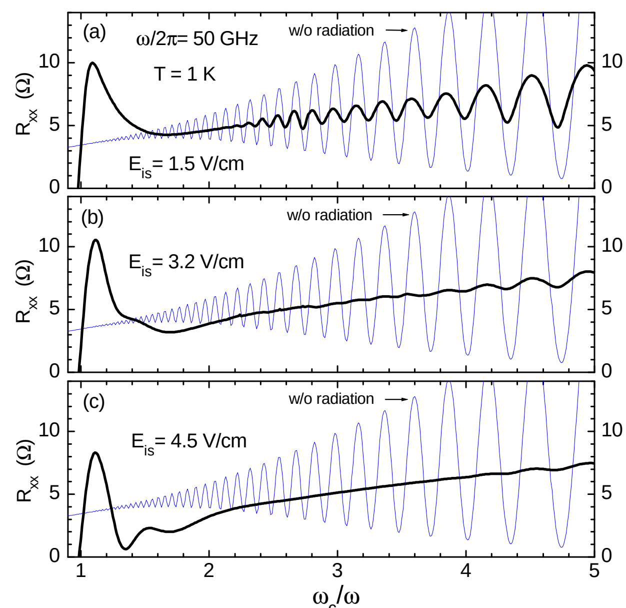

FIG. 2: Magnetoresistivity R_{xx} versus ω_c/ω for the same system as described in Fig. 1, subjected to 50 GHz incident HF fields $E_{\rm is}\sin(\omega t)$ of three different strengths at $T=1\,$K.

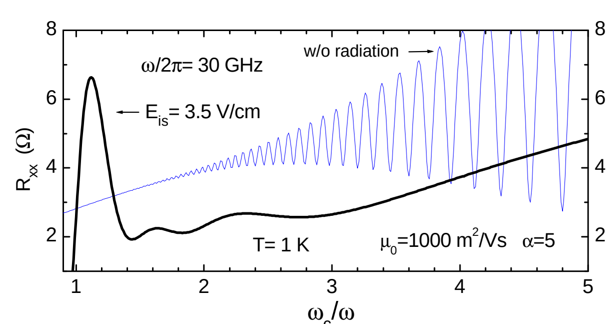

FIG. 3: Magnetoresistivity R_{xx} versus ω_c/ω for the same system as described in Fig. 1, subjected to a 30 GHz incident HF field of $E_{\rm is}=3.5\,{\rm V/cm}$ at $T=1\,$K.

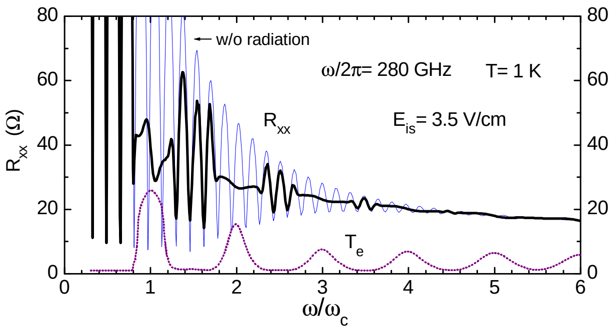

FIG. 4: The magnetoresistivity R_{xx} of a GaAs-based 2DEG with $N_{\rm e}=2.0\times 10^{15}\,{\rm m}^{-2}$, $\mu_0=500\,{\rm m}^2/{\rm Vs}$ and $\alpha=1$, subjected to a 280 GHz HF field of $E_{\rm is}=3.5\,{\rm V/cm}$ at $T=1\,{\rm K}$.

mobility $\mu_0=1000\,{\rm m}^2/{\rm Vs}$, and broadening parameter $\alpha=5$, illuminated by a microwave radiation of frequency $\omega/2\pi=50\,{\rm GHz}$ and amplitude $E_{\rm is}=0.5\,{\rm V/cm}$ at lattice temperature $T=1\,{\rm K}$. The energy absorption rate $S_{\rm p}$ exhibits a large main peak at cyclotron resonance $\omega_c/\omega=1$ and so does the electron temperature $T_{\rm e}$. For this GaAs system, $\beta=0.65$, $a_{\rm inter}=1.9$, and $a_{\rm intra}=2.4$. We can see that, at lower magnetic fields, especially when $\omega_c/\omega<1.5$, the system absorbs enough energy from the radiation field via inter-Landau level transitions and $T_{\rm e}$ is significantly higher than T, with the maximum as high as 21 K around $\omega_c/\omega=1$. With increasing strength of the magnetic field, the inter-Landau level transition weakens and the absorbed energy and electron temperature decreases rapidly. Since the intra-Landau level transitions begin to appear at $\omega_c/\omega>2.4$, there is a magnetic field range within which the impurity-assisted photon absorption and emission process is very weak, such that very little radiation energy is absorbed and the electron temperature $T_{\rm e}$ is almost equal to the lattice temperature T. The magnetoresistivity R_{xx} showing in the upper part of Fig. 1, exhibits interesting features. MIMOs clearly appear at lower magnetic fields, which is insensitive to the electron heating even at $T_{\rm e}$ of order of 20 K. SdHOs appearing in the higher magnetic field side, however, are damped due to the rise of the electron temperature $T_{\rm e}>1\,{\rm K}$ as compared to that without radiation. However, in the range of $1.85<\omega_c/\omega<2.4$, where electrons are essentially not heated, the SdHOs are almost not affected by the microwave. When the microwave amplitude increases to $E_{\rm is}=1.5\,{\rm V/cm}$ (Fig. 2a), MIMOs become strong and SdHOs greatly damped. At $E_{\rm is}=3.2\,{\rm V/cm}$ (Fig. 2b), SdHOs almost disappear and both real and virtual multi-photon processes show up in the MIMOs, resulting in a descent of the magnetoresistivity R_{xx} down below the average value of its oscillatory curve without radiation. This magnetoresistivity descent becomes quite strong at $E_{\rm is}=4.5\,{\rm V/cm}$ due to enhanced multi-photon processes as shown in Fig. 2c.

The radiation-induced R_{xx} suppression at $\omega_c/\omega>1$ appears even more remarkable with lower frequency irradiation. Figure 3 shows R_{xx}-versus-ω_c/ω for the same system as described in Fig. 1, subjected to a 30 GHz microwave of strength $E_{\rm is}=3.5\,{\rm V/cm}$ at $T=1\,{\rm K}$. At this frequency, the ranges for intra-Landau level and inter-Landau level single-photon transitions overlap. The enhanced effect of virtual and real multi-photon processes pushes the resistivity R_{xx} down below its zero-radiation oscillatory curve across a wide range of $\omega_c/\omega>1$, in agreement with experimental observations.[11,13] The microwave-induced suppression of the dissipative magnetoresistivity may be further enhanced by the effect of dynamic localization.[30]

The radiation modulation of SdHOs can be seen at lower magnetic field range $\omega_c/\omega<1$ under higher frequency microwave illumination with simultaneously appearing of MIMOs. Figure 4 shows the calculated R_{xx} and $T_{\rm e}$ for a 2D system of electron density $N_{\rm e}=2.0\times 10^{15}\,{\rm m}^{-2}$, linear mobility $\mu_0=500\,{\rm m}^2/{\rm Vs}$ and $\alpha=1$, subject to a 280 GHz microwave radiation of amplitude $E_{\rm is}=3.5\,{\rm V/cm}$ at lattice temperature $T=1\,{\rm K}$. One can clearly see peaks of the electron temperature $T_{\rm e}$ and nodes of SdHO modulation at $\omega/\omega_c=1,2,3,4$ and 5, together with MIMOs. These are in agreement with the experimental observation reported in Ref.10.

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